Kondo effect in a quantum dot molecule

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要旨
磁場中の結合量子ドットの近藤効果についての理論的研究をおこなう。磁気コンダクタンス (MC) は近藤共鳴状態のスペクトル構造を反映していることを示す。ドット間のトンネル結合 V_C がドットと電極の間の結合 Δ (準位のぼけ) よりも小さいときには、近藤共鳴状態がフェルミ面 (E_F) に形成される。ゼーマン効果は近藤効果を弱めるため、負の MC があらわれる。V_C が Δ よりも大きいときには、近藤状態の反結合・結合状態がそれぞれ E_F の上下に形成される。ゼーマン効果はこれらの準位の E_F での重なりを増やすために、正の MC があらわれる。

Introduction

The microfabrication technique on semiconductors has enabled us to make quantum dots with the size of the order of the Fermi wavelength. Such dots are often referred to as "artificial atoms" due to the discreteness of their energy levels. By coupling the artificial atoms,[1] we can fabricate "artificial molecules." Indeed, interdot "molecular orbitals" have been observed experimentally when the tunneling coupling between the dots V_C is sufficiently large.[2] The strength of V_C can be controlled by external gate voltages.

Recently the Kondo effect has been found in single quantum dot systems.[3] The dot-lead coupling plays a role in the Kondo effect, the strength of which is characterized by the level broadening $\Delta = \pi\rho V^2$ where ρ is the density of states in the leads and V is the tunneling probability amplitude between the dot and leads. When a localized spin in a dot is coupled to the Fermi sea in the leads, the dot spin is screened out and a resonant level is formed at the Fermi level E_F. The resonant width is of the order of the Kondo temperature T_K. The conduction electrons can be transported through the Kondo resonant level, which results in the unitary limit of the conductance, $G = 2e^2/h$.[4]

In coupled quantum dots connected in series, the competition between the dot-dot coupling V_C and dot-lead coupling Δ is important. When the dot-lead coupling larger than the dot-dot coupling ($V_C < \Delta$), the Kondo resonances are created between a dot and a lead. The Kondo resonant levels appear at E_F and the electron transport is determined by the hopping probability between the resonant levels. When $V_C > \Delta$, the Kondo levels are split into two, forming bonding and anti-bonding levels. They are located below and above the Fermi level, $E_F \mp T_K\sqrt{(V_C/\Delta)^2-1}$, and consequently the conductance is suppressed. To observe these unique characters of the Kondo resonant spectra directly, we propose a probe for this resonant spectra, a magnetoconductance (MC).

Model

As a model, we consider a symmetric quantum dot dimer connected in series. Each dot has a single energy level E_0 and accommodates an electron with spin up or down. The energy level is split into $E_0 \pm g\mu_B B$ by the Zeeman effect under a magnetic field B. A common gate voltage V_g is attached to the dots to control E_0. Two dots couple to each other with V_C, and to external leads with V. We assume that the intradot Coulomb interaction U is sufficiently large so that the double occupancy of electrons in each dot is forbidden. The interdot Coulomb interaction is neglected.

The Hamiltonian reads

$$\begin{aligned}\mathcal{H}_0 &= \sum_{\substack{\alpha=\mathrm{L,R}\\ k,\,\sigma=\uparrow,\downarrow}} E(k) c^\dagger_{\alpha k\sigma} c_{\alpha k\sigma} + \sum_{\substack{\alpha=\mathrm{L,R}\\ \sigma}} (E_0 + \sigma g\mu_B B)\, C^\dagger_{\alpha\sigma} C_{\alpha\sigma} \\ &+ \frac{V}{\sqrt{2}} \sum_{\alpha,k,\sigma} \left(c^\dagger_{\alpha k\sigma} C_{\alpha\sigma} + \mathrm{H.c.} \right) + \frac{V_C}{2} \sum_{\sigma} \left(C^\dagger_{L\sigma} C_{R\sigma} + \mathrm{H.c.} \right), \end{aligned} \tag{1}$$

where $c^\dagger_{\alpha k\sigma}$ creates an electron in lead $\alpha = L, R$ with energy $E(k)$ and spin σ, and $C^\dagger_{\alpha\sigma}$ creates an electron in dot α with spin σ. The prohibition of double occupancy in each dot is required. To treat this situation, we adopt the mean field theory of the slave boson formalism of the Anderson model.[6]

The linear-conductance G is written as

$$G = \frac{e^2}{h} \sum_{\sigma=\uparrow,\downarrow} T_\sigma(\omega = 0) \equiv \frac{2e^2}{h} T(\omega = 0) \tag{2}$$

with the transmission probability $T_\sigma(\omega)$ for an incident electron with spin σ and energy ω. We have chosen $\omega = 0$ at the Fermi level in the leads.

Results

First, we study the case of $V_C/\Delta < 1$. In Fig. 1(a), the conductance G is plotted as a function of B when $V_C/\Delta = 0.3$. As B increases, G decreases monotonically (negative MC). At $g\mu_B B \simeq T_K$, the Kondo coupling disappears and $G = 0$, where electrons in the dots are isolated from the leads and make a spin polarized state by the Zeeman effect. The inset in Fig. 1(a) shows the transmission probability $T(\omega)$. When $B = 0$, $T(\omega)$ has a single peak at $\omega = 0$ (dotted line). This is because the Kondo resonant levels are formed between a dot and a lead at $\omega = 0$. The electron transport is determined by the hopping between the resonant states, and hence the peak height of $T(\omega)$ is less than unity. When $B \neq 0$, the Zeeman effect splits the Kondo levels by $g\mu_B B$. In consequence $T(\omega)$ has double peaks at $\omega \simeq \pm g\mu_B B$ (solid line). With increasing B, the peaks are separated more, which results in an decrease in $T(\omega = 0)$. This situation is the same in single quantum dots. The Zeeman effect lifts off the degeneracy of the spin states and hence weakens the Kondo effect. In consequence the conductance G decreases with increasing magnetic field.

Next, we study the case of $V_C/\Delta > 1$. In Fig. 1(b), G is plotted as a function of B when $V_C/\Delta = 1.6$. As B increases from zero, G increases (positive MC). This result is in contrast to that in the case of $V_C/\Delta < 1$. At $g\mu_B B \sim T_K$, the Zeeman effect destroys the Kondo coupling and G drops to zero suddenly. The inset in Fig. 1(b) presents $T(\omega)$. When $B = 0$, $T(\omega)$ has double peaks at $\omega = \mp T_K \sqrt{(V_C/\Delta)^2 - 1}$ (dotted line). These peaks correspond to the molecular levels between the Kondo states.[5] When $B \neq 0$, the Zeeman effect splits both of these molecular levels. There are totally four peaks (solid line). As B increases, the middle two peaks are overlapped more at E_F, which leads to an increase in $T(\omega = 0)$.

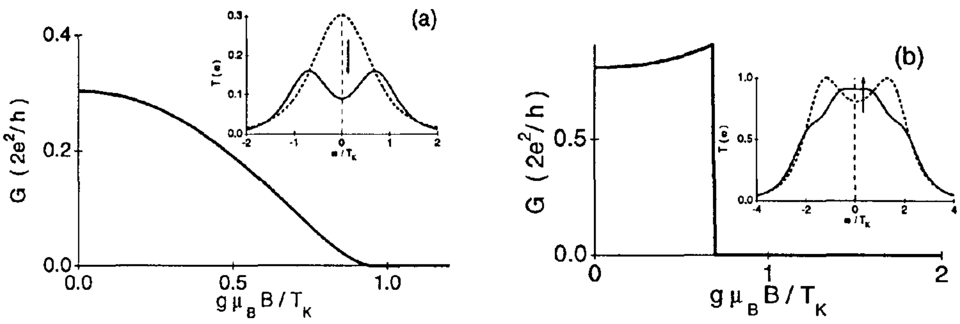

Figure 1: (a) Conductance G as a function of the Zeeman splitting $g\mu_B B$ when $V_C/\Delta = 0.3$ and $E_0/\Delta = -2$. $g\mu_B B$ is normalized by the Kondo temperature T_K at $B = 0$. Inset: Transmission probability $T(\omega)$ with ω being the energy of an incident electron. The dotted and solid lines represent the cases of $B = 0$ and $g\mu_B B/T_K = 0.71$, respectively. (b) G as a function of $g\mu_B B$ when $V_C/\Delta = 1.6$ and $E_0/\Delta = -1.5$. Inset: The dotted and solid lines represent the plot of $T(\omega)$ of $B = 0$ and $g\mu_B B/T_K = 0.63$, respectively.

In conclusions, we have investigated the magnetoconductance in coupled quantum dots in the Kondo region. The MC illustrates peak structures of the Kondo resonant spectra, single peak or double peaks, depending on a ratio of V_C/Δ.

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